Network-Secure Aggregator Operating Regions with Flexible Dispatch Envelopes in Unbalanced Systems

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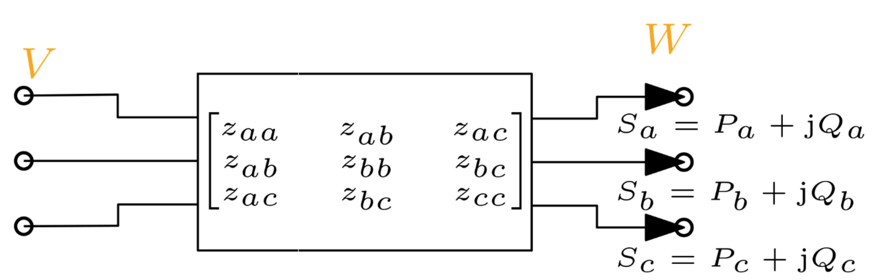
Abstract

Distribution networks need to manage increasing distributed energy resources (DER). While dynamic operating envelopes (DOE) help integrate DER into markets, existing approaches often assume networks are balanced, and this can cause problems in unbalanced networks. We propose the combination of robust aggregator operating regions with flexible dispatch envelopes (RAR-DE), allowing network operators to set sophisticated operating boundaries to aggregators while maximizing market participation. This approach balances market opportunities with network security in unbalanced three-phase systems.

Introduction

DER are expected to play a significant role providing grid balancing services, particularly in Australia as outlined in the AEMO Integrated System Plan. However distribution network capacity is a finite and time-varying resource. Dynamic Operating Envelopes have been adopted in Australia as a mechanism to reserve distribution network capacity for DER, ensuring they can safely participate in wholesale markets.

Algorithms to calculate dynamic operating envelopes often assume distribution networks are balanced. Under this simplification, DER exports generally lead to increased voltage, and imports lead to decreased voltage. Envelopes are therefore deemed safe if network voltages constraints are satisfied when (1) all DER maximise their imports and (2) all DER maximise their exports. However, the relationship between DER exports and voltage is more complex in realistic unbalanced three-phase networks, as demonstrated in Figure 1 lifted from [1] which motivates our work.



$$\frac{\partial |W_a|}{\partial P_a} \approx \frac{-r_{aa}}{U_0}, \quad \frac{\partial |W_a|}{\partial Q_a} \approx \frac{-x_{aa}}{U_0}$$

$$\frac{\partial |W_a|}{\partial P_b} \approx \frac{r_{ab} - \sqrt{3}x_{ab}}{U_0}, \quad \frac{\partial |W_a|}{\partial Q_b} \approx \frac{\sqrt{3}r_{ab} + x_{ab}}{U_0}$$

$$\frac{\partial |W_a|}{\partial P_c} \approx \frac{r_{ac} + \sqrt{3}x_{ac}}{U_0}, \quad \frac{\partial |W_a|}{\partial Q_c} \approx \frac{-\sqrt{3}r_{ac} + x_{ac}}{U_0}$$

Figure 1. Gradient of phase voltage magnitudes with respect to real and reactive load flows on each phase in a 2-bus unbalanced network as presented in related work [1]

The RDOE approach proposed in literature consists of expressing voltage magnitude constraints as inequality constraints with respect to DER exports and imports. This translates to hyperplanes in the space defined by DER exports, producing polytopic feasible regions. Robust DOE proposed in [2] represent hyper-rectangular operating regions contained entirely within the feasible polytope.

Problem Statement

In some unbalanced three-phase networks, hyper-rectangular feasible regions cannot access DER operating points corresponding to high imports and exports. How can we use aggregators to allocate greater capacity in a robust manner?

We address this in our recent paper at the Power Systems Computation Conference 2024 entitled "Network-secure aggregator operating regions with flexible dispatch envelopes in unbalanced systems".

Robust Aggregator Regions Through Polytopic Projection

Our method consists of performing an optimised robust polytopic projection of the network's feasible operating region for DER onto subspaces representing the control actions of each aggregator, as illustrated in Figure 2.

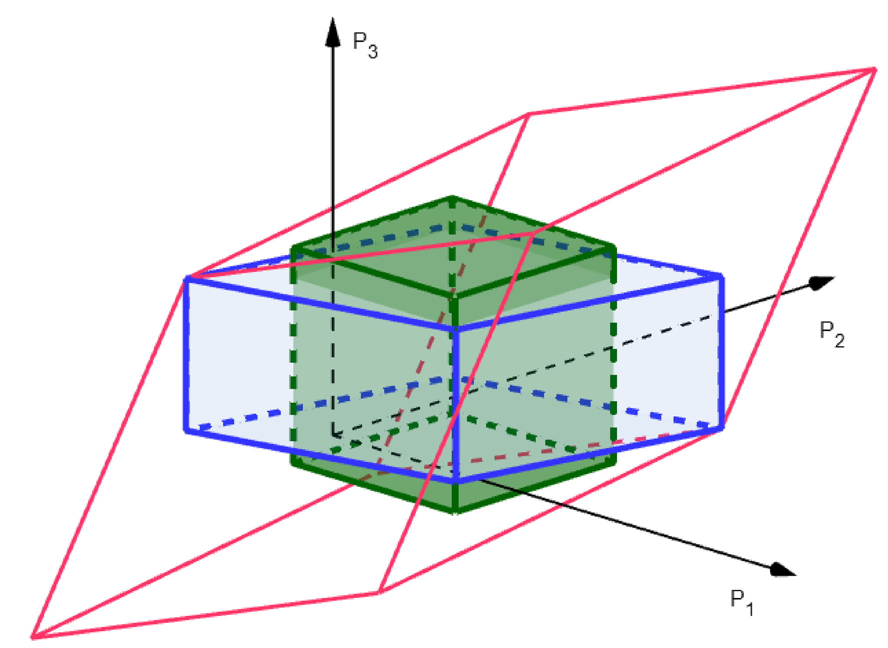


Figure 2. 3-DER illustration of RAR concept in 2-bus sub-network of the IEEE 906-bus network. Network limits are represent by the red polytope, the RDOE solution is represented by the green hyper-rectangle, and the RDOE solution is represented by the blue polytope.

For each constraint defining the underlying feasible region for DER, we bound each aggregator's capacity to increase the LHS of scalar inequality constraints expressed in standard form. Explicitly, for an overall feasible region defined by

$$Av + b \leq 0 \tag{1}$$

We introduce vectors s^a for each aggregator $a \leq N^a$, and require that

$$\forall a \leq N_a : A^a p^a \leq s^a \tag{2}$$

for submatrix A^a and subvector p^a associated to DER under the control of aggregator a. We additionally require that

$$\sum_{a=1}^{N^a} s^a \leq -b \tag{3}$$

Dispatch-Responsive Flexible DER Envelopes

Incorporating large inequality constraint sets into aggregators' dispatch operations may be challenging. Instead, we develop a scheme for aggregators to calculate DER operating envelopes as a function of feeder-scale market dispatch outcomes, as in Figure 3.

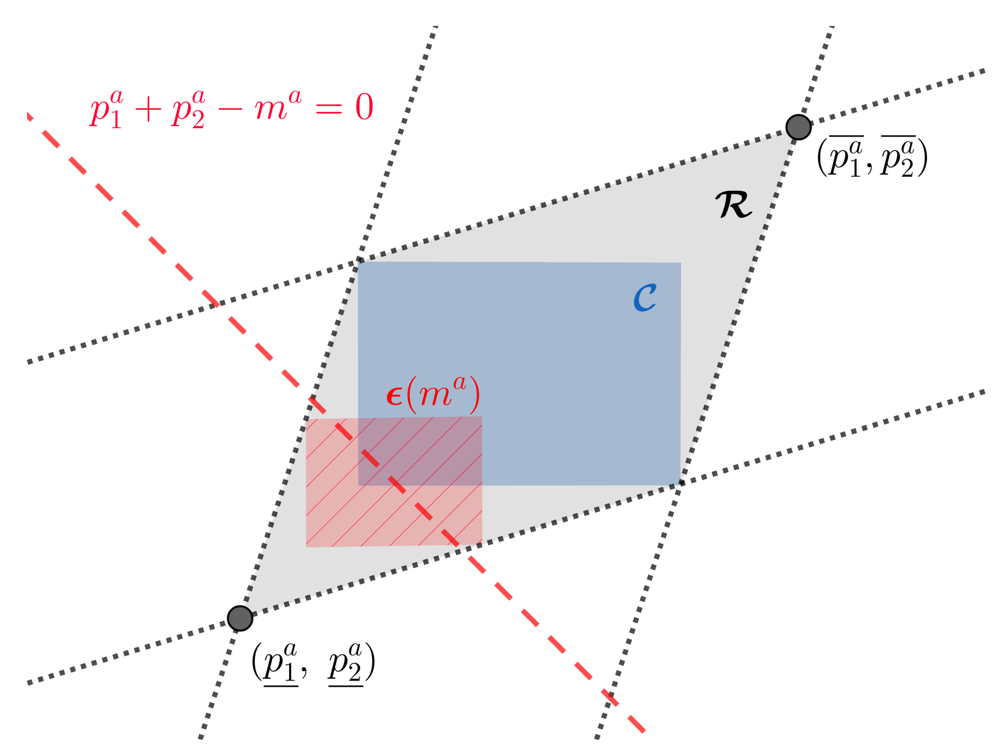


Figure 3. Flexible dispatch envelopes (ϵ) calculated as function of feeder-scale market dispatch outcomes (m^a) to remain within the aggregator flexible region ($\mathcal{R}$). Continuous homothetic transformations of inner region $\mathcal{C}$ towards extreme points must lie in $\mathcal{R}$ due to convexity.

Simulation Results

We compare the conventional DOE approach, the recently proposed RDOE and our RAR-DE approaches in simulations. Using the IEEE European LV Test Feeder[a], applying real load and PV data from trials in Canberra, Australia, we calculate capacity allocations and evaluate network security outcomes in Monte Carlo simulations, to test robustness to potentially unbalanced dispatch by aggregators following plausible disaggregation methods.

Our first set of results in Figure 4 demonstrates that RAR-DE achieves similar capacity allocation outcomes to DOE approaches currently used in Australian trials, which is significantly greater than what is possible under bi-directional RDOE.

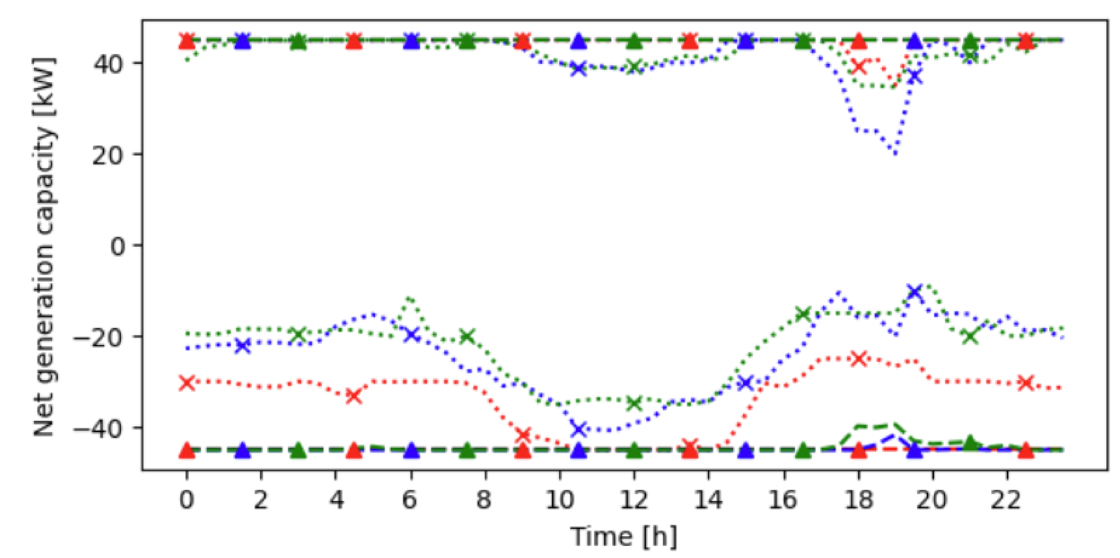


Figure 4. Total capacity $p^a_{\min}, p^a_{\max}$ allocated to aggregators (identified by colour) under **RAR-DE** and **DOE** (dashed, triangles) and **RDOE** (dotted, crosses) approaches.

Our second set of results in Figure 5 demonstrates that our RAR-DE approach provides network security guarantees for potentially unbalanced three-phase dispatch outcomes, modelling various disaggregation strategies adopted by aggregators.

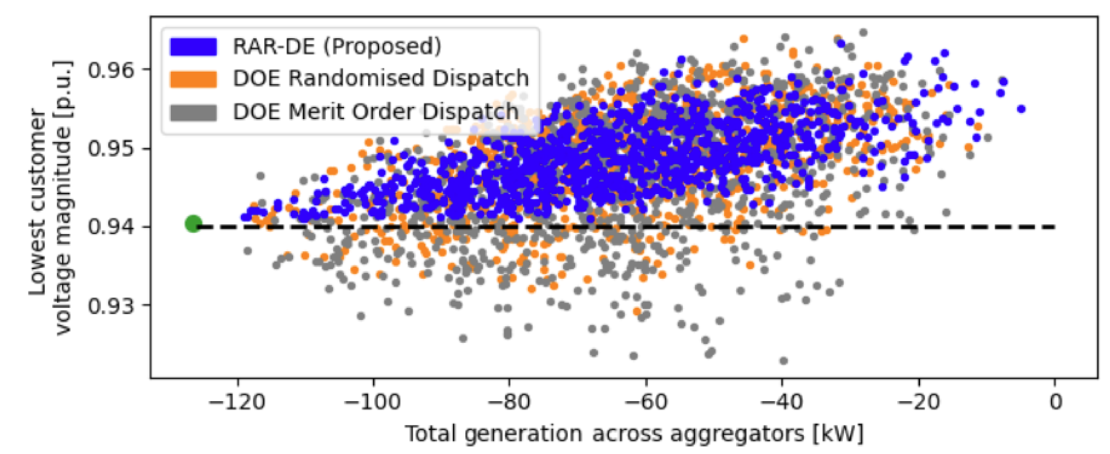


Figure 5. Lowest recorded voltages at customer locations in the European Low Voltage Test Feeder in Monte Carlo simulations, as a function of total aggregator dispatch at 7:00pm

Conclusion

Our simulations have demonstrated that our proposed approach combines (1) the favourable capacity allocations of DOE calculated assuming balanced network operation, with (2) the robust network security guarantees of the recently proposed RDOE method.

References

[1] Bin Liu and Julio H Braslavsky.
Sensitivity and robustness issues of operating envelopes in unbalanced distribution networks.
IEEE Access, 10:92789–92798, 2022.

[2] Bin Liu and Julio H Braslavsky.
Robust dynamic operating envelopes for der integration in unbalanced distribution networks.
IEEE Transactions on Power Systems, 2023.

[a] In our simulations Kron's reduction has been applied to the impedance data on the assumption that the neutral is perfectly grounded everywhere

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